

# Difficulties of the traditional PhC-based superprisms

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## Abstract

This paper is to discuss the difficulties of the traditional photonic crystals (PhC) -based superprisms.

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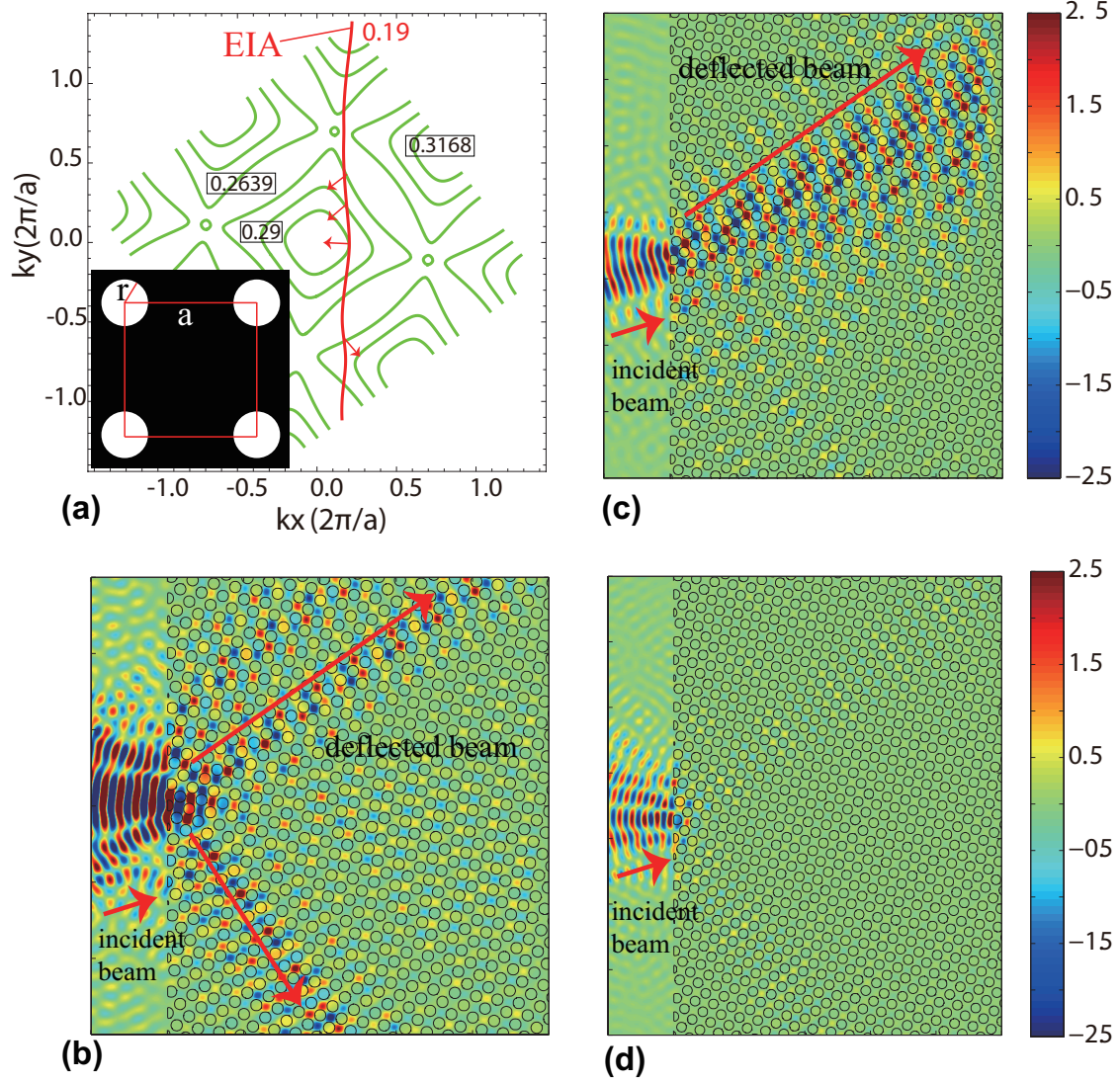


FIG. S1. (a) The equi-incident angle (red line) and the EFCs (green line) of the square lattice PhC in the first BZ. The inset is the structure of the square lattice PhC. The red arrows indicate the directions of the group velocity of light at the different frequencies  $\tilde{\omega}_1 = 0.2639$ ,  $\tilde{\omega}_2 = 0.29$ , and  $\tilde{\omega}_3 = 0.3168$ , respectively. (b) The irregular beam generation in the PhC at the frequency  $\tilde{\omega}_1 = 0.2639$ . (c) The beam divergence in the PhC at the frequency  $\tilde{\omega}_2 = 0.29$ . (d) The wavelength channel dropout at the frequency  $\tilde{\omega}_3 = 0.3168$ . The frequencies are in units of  $2\pi c/a$ .

The traditional PhC-based superprisms always face three difficulties: (I) irregular beam generation, (II) beam divergence, and (III) the wavelength channel dropout in the operating frequency channel. The negative effect generated by these unfavorable factors can also be seen at Fig.4 in the reference [1], and in the reference there are also some explanations on

these difficulties.

To show the difficulties of the traditional PhC-based superprisms more clearly, here we give an example. First, consider a “sharp-corner” superprism based on a rod-type PhC made of a square lattice with the lattice constant  $a$ , the rod radius  $r = 0.35a$  and the refractive index  $n = 3.4$ , whose structure and equi-frequency contours (EFCs) are shown in Fig.S1(a). The best wavelength-sensitivity effect of the sharp-corner superprism can be found around the sharp-corner region of the EFCs. In order to utilize the superprism, we calculate the equi-incident angle (EIA), as shown in Fig.S1(a) indicated by a red line. The EIA line and the high resolution of the superprism are matched together by rotating the PhC  $45^\circ$ . The directions of the group velocity of light in the PhC at different frequencies are labeled by red arrows, as shown in Fig.S1(a). Second, we show the three difficulties of the superprism. Figures S1(b), (c) and (d) show the the field distributions, which correspond to the irregular beam generation, the beam divergence, and the wavelength channel dropout, respectively. From Fig.S1(b) to (d), the corresponding operating frequencies are  $\tilde{\omega}_1 = 0.2639$ ,  $\tilde{\omega}_2 = 0.29$ , and  $\tilde{\omega}_2 = 0.3168$ , respectively. Here all the frequencies are in units of  $2\pi c/a$ , and all the field distributions are calculated by the finite-difference time-domain (FDTD) method.

When the operating frequency is close to the edge of Brillouin Zone (BZ), the incident light beam from homogenous media may much more easily couple to multi-modes of the PhC in higher order BZ, besides the one in the 1st BZ. In this case, the multi-refraction problem can be generated. The irregular beams always appear due to the multiply cross points induced by the parallel component of the wavevector, as shown in Fig.S1(a). Although in some special cases the irregular beam can be small[1], we notice that, generally the intensities of irregular beams are out of control. Physically, in order to suppress the irregular beams generation one possible solution is to choose the operating region far away from the edge of BZ.

When the operating frequency has a big curvature iso-frequency contour in the BZ, for instance,  $\tilde{\omega}_2 = 0.29$  in Fig.S1(a), the deflected beams in the PhCs would be broaden. Unfortunately, the sharp-corner superprism always have operating frequencies near the sharp-corner region whose iso-frequency contours must have big curvature. Therefore the beam divergence is unavoidable.

When the operating frequency is at the corner of EFCs, such as the operating frequency is  $\tilde{\omega}_2 = 0.3168$  in Fig.S1(a), the light cannot propagate in the PhC, as shown in Fig.S1(d). This

is because the operating frequency at the cross point cannot clearly define the wavevector. This fact makes the operating frequency cannot be switched successively, i.e., some of the wavelength channel is lost[1]. We call this wavelength channel loss as “wavelength channel dropout”.

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[1] T. Baba, and M. Nakamura , IEEE Journal of quantum electronics, **38**, 909(2002)

# Enhanced wavelength sensitivity of self-collimated superprism effect for high-performance demultiplexer

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In this paper we demonstrate a frequency-sensitive self-collimation, which we call *frequency-sensitive self-collimation* (FSSC), can be founded in a rectangle-lattice rod-type photonic crystal (PC). Some properties that are favorable for designing photonic devices based on superprism are found in the PC that FSSC exists. Also, we present a design for the three channels demultiplexer based on the superprism of PC with FSSC.

Superprism effect [1, 2] in photonic crystals (PCs)[3] have drawn much attention due to their great potential applications in integrated photonic circuit devices, such as a demultiplexer[4–6] that is used for the separation of wavelength channels of an optical signal. The traditional design for such demultiplexers is mostly using the superprism effect within sharp corner regions of the dispersion surfaces of PCs. For convenience, we refer such superprism effect to “sharp-corner superprism effect”. Such traditional demultiplexers using the sharp-corner superprism effect exhibits high sensitivity on wavelength. However, these traditional demultiplexers face with several major difficulties for the practical applications, such as the beam divergence, the irregular beam generation, and the wavelength channel dropout [see the “Difficulties of the traditional PhC-based superprisms” discussed in the above article]. The beam divergence and the irregular beam generation not only negatively impact the wavelength resolution, but also result in a higher crosstalk that is a drawback for integrated photonic circuits. The wavelength channel dropout would cause a high non-absorption loss of the optical signal in a specific wavelength region, which may bring down the demultiplexers’ performance. These difficulties are unfortunately very hard to avoid for the traditional demultiplexers because of the intrinsic physical properties of the sharp-corner superprism effect.

To circumvent these difficulties, recently, another solution[7] has been proposed for the demultiplexer. In the solution, instead of the traditional sharp-corner superprism effect, the self-collimated superprism effect is used. This approach has many advantages, e.g., it has been predicted to be able to overcome the wavelength channel dropout and suppress the beam divergence. However, a cost of this solution is that the wavelength resolution is lower, since the angular dispersion is reduced near the self-collimated region. In addition, since the self-collimated superprism effect they use is operating in the region near the edge of Brillouin Zone, the irregular beam generation may also be unavoidable.

Reviewing these existing efforts for the demultiplexers, it is natural to wonder whether we can find an approach that not only can reduce the beam divergence, but also have high wavelength resolution and can suppress the irregular beam generation. In this letter, we will present our approach to serve this purpose.

The main idea of this work is from our study on the effect of a saddle point Van Hove singularity located near the self-collimated region in the equi-frequency contours (EFCs) of PCs. We find that the saddle point Van Hove singularity near the self-collimated region can lead to a situation that the self-collimated beams are extremely wavelength-sensitive. As a consequence, the performance of the self-collimated superprism can be greatly enhanced via a saddle point Van Hove singularity. Therefore, the key to our approach for a superprism is that a saddle point Van Hove singularity should be located at the position very close to the self-collimated region in the EFCs.

In order to illustrate the principle of our approach more clearly, here we present a typical example. The model is schematically shown in Fig.1(a), in which a two-dimensional (2D) rod-type photonic crystal is made from a rectangular lattice with  $b = 1.8a$ , radius  $r_h = 0.32a$ , and the refractive index  $n = 3.4$ . From the EFCs in Fig.1(a), we can find there is a region (inside the rectangle) in which the curvatures are nearly zero around at the frequency  $\tilde{\omega}_s = 0.371(2\pi c/a)$ . Obviously, this region corresponds to a good self-collimated region, with more details of its EFCs shown in Fig.1(b).

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The position of the saddle point Van Hove singularity is also calculated, which is located very near the self-collimated region as shown in Fig.1(b). Next, we find an equi-incident-angle path (EIAP) that crosses the self-collimated region, which can be seen in Fig.1(b). So, the operating region of the superprism is the region where the EIAP crosses the self-collimated region associated with the saddle point Van Hove singularity. In the operating region, we think the superprism can exhibit high performance.

Usually, the performance of a superprism can be described by the parameters  $p$ ,  $q$ , and  $r$  introduced by Baba *et al.*, where  $p = \partial\theta_c/\partial\theta_i$  is the beam broadening factor,  $q = \partial\theta_c/\partial\tilde{\omega}$  is the generalized dispersion factor, and  $r = q/p$  is the resolution parameter. Here,  $\theta_i$  is the propagation angle of the incident beam,  $\theta_c$  is the propagation angle of the refractive beam, and  $\tilde{\omega}$  is the normalized frequency in units of  $2\pi c/a$ . A high-performance superprism should have smaller values of  $p$ , and larger values of  $q$  and  $r$  in its operating region. For the 2D photonic crystal shown in Fig.1(a), the  $p$ ,  $q$ , and  $r$  are calculated and their logarithmic scale color maps are shown in the figures 2(a)-2(c), respectively. In the operating region, we can see that  $p$  is very small ( $p \simeq 0$ ), but  $q$  and  $r$  are very large. This corresponds to a near perfect collimation. This is one of the largest values reported so far for a wavelength-sensitive superprism effect in 2D PCs.

This great performance enhancement can be understood as follows.

First of all, we should choose an appropriate operating region in the EFCs for the superprism. For this goal, first, we should seek out an appropriate self-collimation region that has a saddle point Van Hove singularity nearby; second, we should find out an equi-incident-angle path (EIAP) that crosses the aforementioned self-collimated region. After that, the self-collimated region where the EIAP crosses and has a saddle point Van Hove singularity nearby, is the appropriate operating region we choose for the superprism.

Also, we find the condition that a saddle point Van Hove singularity appears near the self-collimated region can be much more easily realized in the rod-type PCs with a rectangular lattice. So, this kind of PCs can be used to design the wavelength-sensitive demultiplexers, based on the self-collimated superprism effect associated with a saddle point Van Hove singularity.

The super-collimation[8–10] has been studied, which predicated to be very sensitive to the frequency. Recently, we found the super-collimation in rectangle lattice rod-type PC, which is more sensitive to frequency than super-collimation have been reported, we call the *frequency sensitive self-collimation* (FSSC). Most of demultiplexers have reported based on the superprism focused on the frequency sensitivity, but the beam collimation was ignored which may lead to the large size of the demultiplexer, which is not appropriate for the integrated photonic circuit. Recently, we find that self-collimation is very sensitive to frequency in rectangle lattice with appropriate length-width lattice ratio PC, which we call this phenomena FSSC. The equi-frequency contours (EFC) of this kind of PC are shown in Fig.1. The property of the EFC is that the curvature is changing from negative to positive, as shown in Fig.1 frequency around  $\tilde{\omega} = 0.371$  with frequency changing  $\delta\tilde{\omega} = 0.006$ . More importantly, the curvature of the EFC with  $\tilde{\omega} = 0.371$  is zero, which implies good self-collimation properties in this region. The curvature[12] of the EFCs being defined is:

$$\kappa = \frac{d^2k_y}{dk_x^2}|_{\omega_0}/[1 + (\frac{dy}{dx}|_{\omega_0})^2]^{\frac{3}{2}} \quad (1)$$

Its implicit formula[12] is

$$\kappa = \frac{\omega_{xx}\omega_{yy}^2 + \omega_{yy}\omega_{xx}^2 - 2\omega_{xy}\omega_{xx}\omega_{yy}}{\omega_{xx}^2 + \omega_{yy}^2} \quad (2)$$

which we can get the numerical form the EFC which we get it by plane wave expansion[13]. The key point of the FSSC is the  $\kappa$  changing from negative to positive with frequency changing, moreover we find the  $\kappa$  of the given EFC always change and at some region of this EFC the curvature of the EFC is zero, in other words, there exists flat region which means the electromagnetic wave can have good self-collimation(SC) with this incident  $k$ . We call this SC region localized SC region. In this region, we can utilize it to keep the electromagnetic wave good collimation property with less spreading.

## I. MODEL AND ANALYSIS

The two unfavorable factors mentioned above, we have found in most PC structures. But recently, we find the beam sensitivity and self-collimation can be matched in rectangle lattice PC because of the frequency sensitive self-collimation and localized self-collimation. We calculate the superprism parameters of the rectangle lattice air-rod type PC (Fig.2(a)) in which the FSSC we find. The FSSC region are shown in red rectangle region as shown in Fig.2(b), the curvature of the rectangle EFC changes from negative into positive. In this region, the self-collimation are very

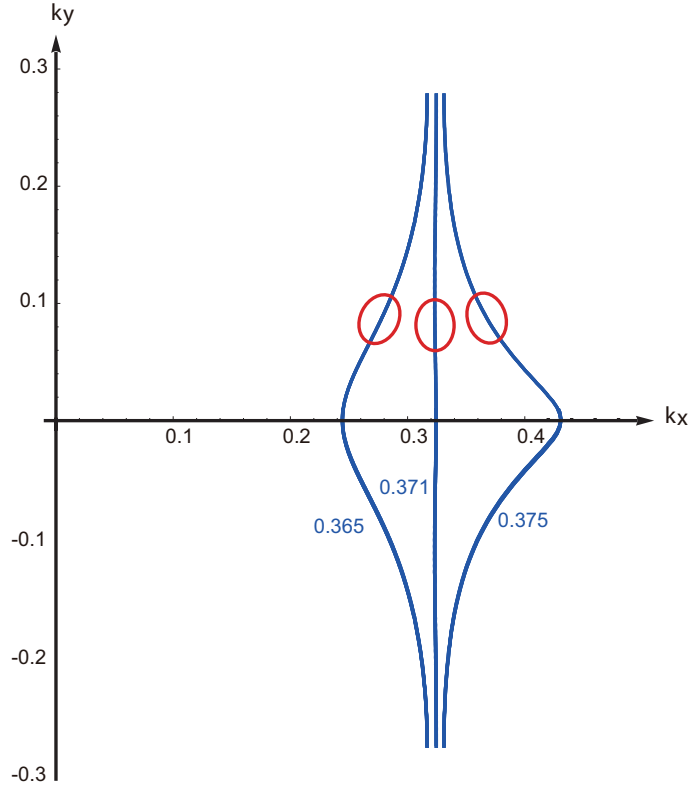


FIG. 1: Schematic illustration of the FSSC and localized SC in PC. Localized SC regions are labeled by circle.

sensitive to the frequency. The superprism parameters of this PC we calculated are shown in Fig.2(c)-(e). There really exists high wavelength resolution in this kind PC, as red region shown in Fig.2(e).

The incident angle, resolution of the rectangle lattice PC and the FDTD simulation of superprism are shown in Fig.3. As shown in Fig.3(a), the green lines are the EFC, the white circle are the localized self-collimation, and the light region are the high resolution  $r$  in the a quarter BZ region. The beam deflected angle are  $52.11^\circ$  as frequency changing from  $\tilde{\omega}_1 = 0.365$  to  $\tilde{\omega}_2 = 0.375$ . The beam propagates with less diffraction, about  $0^\circ$  with propagating length  $30a$ , in other words, the beam collimation property keeps very well at the same time, as shown in Fig.3(b), (c), (d). The width of incident beam is about  $4a$ . This is the largest deflected angle and the best collimation with less diffraction we find. If we set the  $\tilde{\omega} = 0.375$  corresponding to the wavelength  $\lambda = 1.55\mu m$ , the channel number we get in the way[15]  $N_c = \theta_T/\delta$  is 135.

## II. DEMULTIPLEXER

Based on the results we have got, high resolution superprism parameter and good collimation with less beam diffraction property could be found in rectangle lattice PC which have FSSC and localize self-collimation properties. Furthermore, the three channel wavelength demultiplexer is designed. In order to keep the wavelength dividing in the air, the structure we designed in semi-circle PC, as shown in Fig.4(a). Some detectors are placed at the periphery, then the results are shown in Fig.4(b). Three gaussian beams with different frequency are divided clearly at different location of the circle which corresponding to three different angles. Form the numerical results Fig.4(b), we can also see that the deflected beams almost keep the same width as that of the incident beam, which implies that the rectangle lattice PC demultiplexer keeps the high resolution of superprism and the property of the collimation. The material of the incident waveguide we chose is the same as the rod that consists with PC, in that way, the energy can couple into the PC easily.

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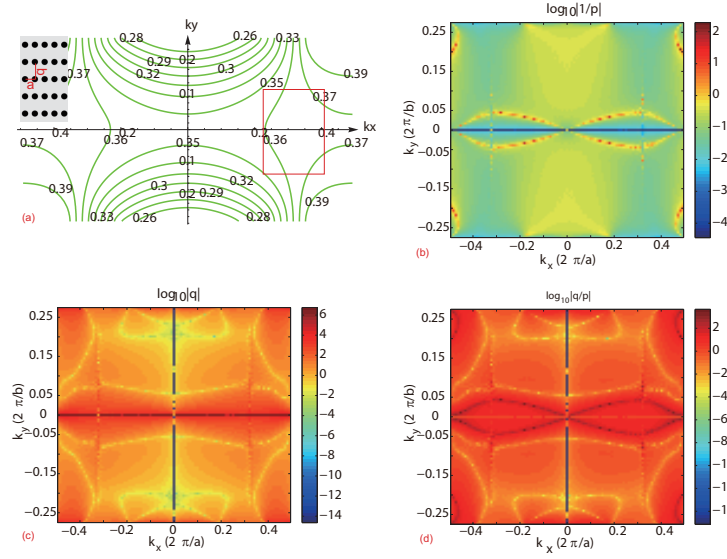


FIG. 2: (a) EFC distribution of the rectangle lattice PC. The inset picture is structure of the rectangle lattice PC. The FSSC region and localized SC regions are labeled by red rectangle. (b), (c) and (d) are the superprism parameter for  $1/p$ ,  $q$ ,  $r$  of rectangle lattice PC with ratio  $b/a = 1.8$ .

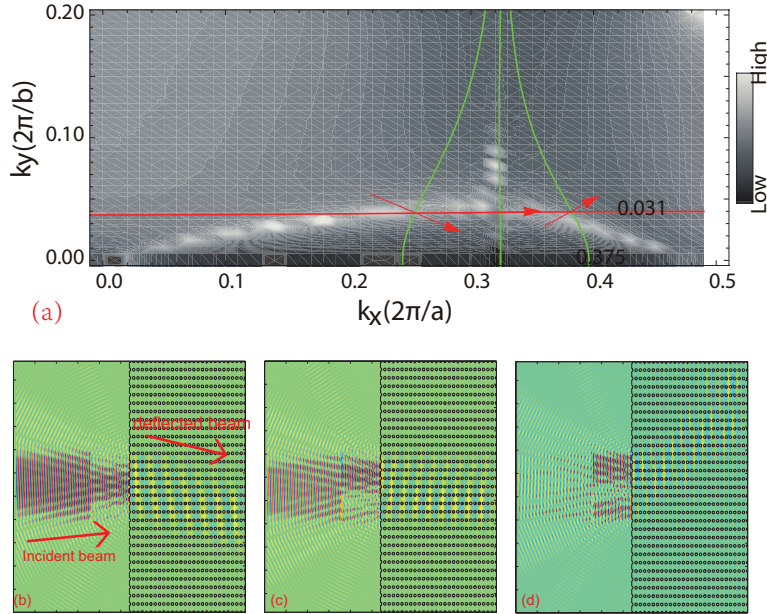


FIG. 3: (a) The resolution, the equi-incident angle distribution and the EFC of the rectangle lattice PC  $r$  in a quarter BZ. The white region is localized self-collimation region. (b), (c), (d) are corresponding to the FDTD simulation result with frequency  $\tilde{\omega}_1 = 0.365$ ,  $\tilde{\omega}_2 = 0.371$ ,  $\tilde{\omega}_3 = 0.375$ , respectively.

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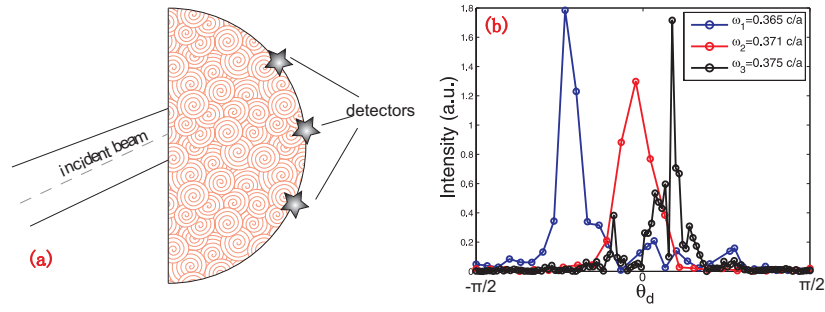


FIG. 4: (a) Structure of demultiplexer we designed. (b) The deflected beam intensity distribution with the angle which is the angle of the circle of demultiplexer. Three peaks at different of the angle are clearly seen.

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